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THE USE OF ULTRASONIC GAS FLOW METERING TECHNOLOGY FOR THE DEVELOPMENT OF ACCURATE ENERGY METERS FOR NATURAL GAS

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1. Introduction

Gasunie Research gained their years of experience in efficient energy utilization, gas transport and gas measurement as the in-house laboratory for N.V. Nederlandse Gasunie. This company, which was an integrated gas transport and trading company until the beginning of 2002, has been one of the largest gas suppliers in Europe for several decades. As part of this company, Gasunie Research has always striven to guarantee the continuity of the gas supply, to ensure the safety of gas transport and to enhance the added value of natural gas as a fuel. Gasunie Research developed a wealth of new technology for domestic, commercial and industrial end users, and for the energy sector itself. The expertise that Gasunie Research has acquired through these activities and the years of practical experience is now made available to third parties.

Energy measurement is one of the main tasks of gas transport companies. New challenges in the gas world confront gas transport companies with new requirements regarding energy measurement. (e.g. the variation in gas composition will be larger and will occur more frequently). These changes are the driving force for a number of new developments in energy metering. Present energy measurement systems for natural gas comprise of volume metering, volume conversion from field conditions to reference conditions and calorific value determination at reference conditions. The calorific value, H_{SR}, is mostly determined by compositional assay using a process gas chromatograph. The volume is commonly measured by a turbine flow meter, an ultrasonic flow meter or an orifice plate. The volume conversion factor is mostly determined from thermal equations of state, using the gas composition or some gas properties as input. The cost of ownership for accurate energy meters based on process gas chromatographs is high. These high costs were the main reason for Gastransport Services (the transportation company of N.V. Nederlandse Gasunie) and Ruhrgas AG to join forces on the development of new energy flow measurement methods.

These new methods are based on the measurement of three suitable properties (e.g. physical properties or component concentrations) and an accurate correlation between these properties and the gas composition. The inferred gas composition is used to compute a variety of gas properties like the superior calorific value, the density, the compression factor under reference and field conditions and the Wobbe-Index.

Within the joint project Gasunie Research focussed on the development of an energy meter based on velocity of sound measurements. The new meter is based on the measurement of the velocity of sound at high pressure (VOS_{high}), the velocity of sound at low pressure (VOS_{low}), and the molar fraction carbon dioxide (X_{CO2}). This combination is particularly suitable for stations with high pressure gas available ($P > 40$ bar).

In this paper results for the superior calorific value of natural gas obtained with both a dedicated double velocity of sound meter and with velocity of sound measurements obtained by an ultrasonic gas flow meter will be discussed.

1.1. Advantages of the new correlative energy meter

The new energy meter is based on instruments and components, which have already been in use in the gas industry in other applications for a number of years. Therefore, these components have already proven to be highly accurate and reliable and if necessary at all, only required a low calibration frequency. This is probably one of the reasons that during the test period of more than one year, no instruments needed to be recalibrated and not a single malfunctioning of the applied instruments did occur.

The new energy meter has a compact design and can be easily mounted near the sampling point, making the additional investment costs relatively low. Finally, the new meter combines low gas consumption with a fast measuring cycle and is therefore particularly suited for process control in for example blending stations.

2. Project Objectives

The objective of the overall project was to develop an energy meter based on the measurement of three properties using two velocity of sound measurements. Consequently, it was necessary to construct an accurate velocity of sound meter first. Laboratory and field tests were conducted to evaluate the performance of the energy meter and to compare the performance of the new system with the highly accurate Daniel Danalyzer field gas chromatograph model 500, which is used for billing purposes by Gastransport Services in the Netherlands. Further improvements were made to obtain a high performance Wobbe meter, which is currently being tested in a field test at a blending station and compared with a traditional Wobbe Index meter. The Wobbe Index is defined as the ratio of the superior calorific value to the square root of the relative density, d, of a gas:

$$\mathbf{W_i = H_{SR} / \sqrt{d}} \qquad (1)$$

with

$$\mathbf{d} = \rho_{\mathbf{R,gas}} \mathbf{/} \rho_{\mathbf{R,air}} \qquad (2)$$

The Wobbe Index is a measure for the amount of energy delivered to a burner via an injector. Two gases of differing composition and calorific value but having the same Wobbe Index will deliver the same amount of energy for any given injector at a given injector pressure.

Finally it was investigated whether it is possible to use velocity of sound data generated by an ultrasonic flow meter to calculate accurate values for the superior calorific value at field conditions.

3. Theoretical background and calculation procedure

The correlation method is based on the assumption that a natural gas can be characterized as a four-component mixture consisting of nitrogen, carbon dioxide and an equivalent hydrocarbon gas (methane + higher hydrocarbons). The same approach is already used in the SGERG equation [1], [2]. A dedicated iterative method was developed on the basis of this correlative method [3].

As stated before, the correlation method requires measured values of three independent gas properties. Preferred are properties, which can be measured with relatively simple but accurate and reliable sensors. The sensors need to be easy to maintain and the accumulated costs of ownership needs to be considerably lower than the present energy measurement methods.

The joint project of Gastransport Services and Ruhrgas revealed a number of combinations of measurable gas properties [4], [5], [6], [7]. Especially the combination of velocity of sound at low pressure, velocity of sound at high pressure and molar fraction carbon dioxide appears to be attractive, and is the reason for a dedicated discussion in this paper.

A schematic overview of the calculation method is shown in figure 1. Input data are the high pressure VOS with pressure and temperature, low pressure VOS with pressure and temperature and the CO_2 concentration. The high pressure VOS can be measured by a highly accurate VOS-meter as well as an accurate ultrasonic gas flow meter. The iterative calculation procedure has the following sequence: an initial gas composition is used to compute the velocity of sound (VOS). Subsequently, the computed velocity of sound is compared with the measured velocity of sound. Because the velocity of sound is a function of P and T, these two parameters have to be measured with high accuracy as well.
Depending on the differences, the composition is adjusted and the calculation loop is repeated until the absolute value of the differences between computed and measured velocities of sound (VOS) are less then 0.005%. The final gas composition is used to compute the superior calorific value under reference and field conditions, H_{SR} and H_S, respectively. Also, the densities, ρ_R and ρ, under reference and field conditions, respectively, can be calculated by using the measured pressure and temperature at pipeline conditions. The total energy flow can be computed by multiplying the calorific value at field conditions and the gas flow rate.

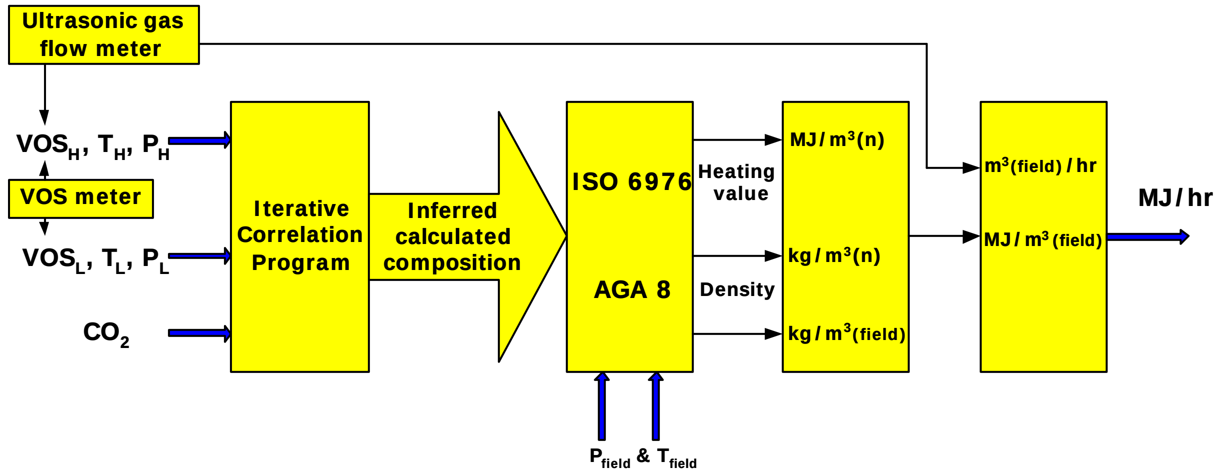

Figure 1. The method used to calculate the energy flow and gas properties like the calorific value, density and Wobbe Index from three independent gas properties

The correlation model itself was validated with several gases of known composition abstracted from the list of GERG-gases [9] and with a number of test gases. These gases were analysed with a laboratory GC, according to ISO 6974 and the gas properties were calculated using ISO 6976. The known composition was used to calculate H_{SR} as well as the velocity of sound at low and high pressure. Both velocities of sound and the molar fraction CO_2, were used as input parameters for the correlation model.
Calculations showed that the correlation model, based on two velocity of sound measurements and the molar fraction carbon dioxide, predicts the superior calorific value within 0.1% for the whole range of natural gases.
Also important is the sensitivity of the correlation model with respect to small deviations (due to random or systematic errors) in the measured data. Calculations showed that 0.01% deviation in VOS_{high} and VOS_{low} result into an error in H_{SR} of -0.11% and +0.12% respectively. The error in H_{SR} increases if the difference in pressure decreases at which VOS_{high} and VOS_{low} are measured. Deviations in the measured temperature of the gas also result in relatively large errors in H_{SR}. A deviation of 0.01% (30 mK) in T_{high} and T_{low}, the temperature of the high pressure and low pressure velocity of sound measurement, induces an error in H_{SR} of +0.07% and –0.06%, respectively. Deviations in pressure and molar fraction CO_2 result in much smaller errors in H_{SR}. If VOS_{high} and VOS_{low} deviate both +0.01%, the errors in H_{SR} are almost

compensated (-0.11% + 0.12% = 0.01%). The same situation occurs for T_{high} and T_{low}. Therefore, systematic errors in velocity of sound and temperature measurement (for example due to calibration), result in relatively small errors in the calorific value.

4. The energy meter based on the double VOS-meter

4.1 The instrument.

Application of velocity of sound as a measurement in correlative energy metering implicates the following requirements for VOS-meters: (a) high accuracy (better than 0.03%) and very high reproducibility (better than 0.005%); (b) because the VOS-meters need to operate with a continuous gas flow, a small internal volume is important for low gas consumption; (c) the temperature and pressure of the gas in the VOS-meter have to be known accurately and thus only changes in temperature and pressure at a time scale relative large to the measurement time (seconds) are allowed. Besides, the temperature and temperature profile of both VOS-meters should preferably be identical.

To fulfil the requirements mentioned above, Gasunie Research developed in cooperation with Instromet a new low volume, highly accurate VOS-meter [11]. The new VOS-meter is based on transducers and electronics used in the new Q.SONIC-3S compact ultrasonic flow meter of Instromet Ultrasonics. Two identical VOS-meters were applied in the energy meter, one for the high pressure measurements and one for the low pressure measurements.

A schematic view of the correlative energy meter is shown in figure 2. Natural gas has to be available at a pressure above 40 bar. The pressure is reduced, preferably by low volume reducers, to approximately 40 and 5 bar. Both the high pressure and low pressure gas flow passes a heat exchanger before entering the VOS-meters. The heat exchangers and VOS-meters are placed in an isolated box. The gas flow is controlled by needle valves downstream of the VOS-meters. Part of the low pressure gas is diverted to the CO_2-meter.

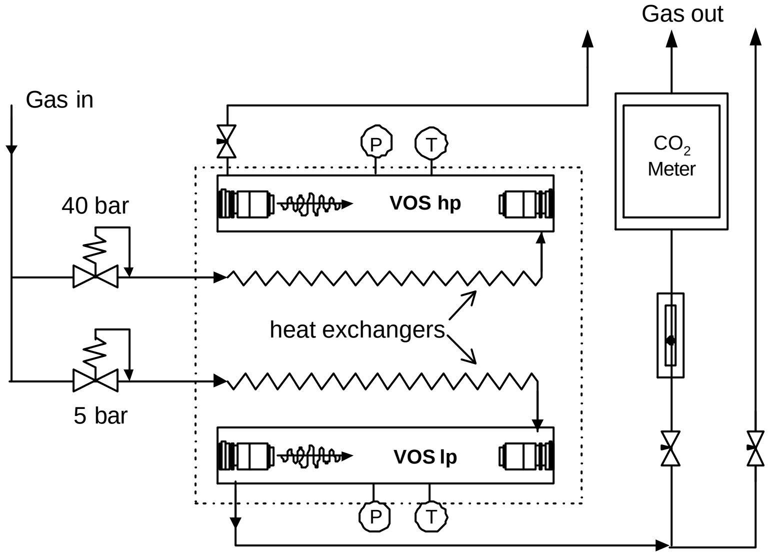

Figure 2: The energy meter based on two velocity of sounds and the CO_2 measurement. The components within the dotted lines are placed in an isolated box, which has the possibility for temperature conditioning

The CO_2-meter applied in the correlative energy meter, is a commercially available non-dispersive, dual wavelength near infrared meter, type AGM10, range 0 – 5 mol% CO_2, from Sensor Europe. The meter is kept at a constant temperature of 50 °C and is equipped with pressure compensation. The measurement uncertainty is 0.05 mol% and the reproducibility is 0.01 mol%.

The pressure is measured with Yokogawa EJA310A absolute digital pressure transmitters with an intrinsically safe approval. The uncertainty of these transmitters is 0.01 bar and the reproducibility is 0.005 bar. The temperature is measured with 1/10 DIN 4-wire PT100's and Moore Industries TDZ digital and intrinsically safe temperature transmitters. The uncertainty in the temperature measurement is 0.03K, whereas the reproducibility is better than 0.01K.

The gas consumption is approximately 2.5x10^{-3} m^3/hr for both VOS-meters, resulting in a residence time of approximately 30 seconds. A data acquisition system stores the required measurement data: VOS_{high}, T_{high}, P_{high}, VOS_{low}, T_{low}, P_{low} and X_{CO2} and subsequently a computer system calculated the results (gas composition, calorific value, density and compressibility under reference conditions).

4.2 The first results

In figure 3 the difference is shown between the calorific value under reference conditions measured with the correlative energy meter and measured with a HP 5890 laboratory GC (with analysis according to ISO 6974 and gas property calculation according the ISO 6976). Gases with large variations in composition were applied. The calorific value of these gasses varied between 33 and 45 MJ/m^3(n). This test was performed to show that this correlative technique applies for all natural gases.
The preliminary results in figure 3 indicate that the maximum deviation of H_{SR} calculated from two VOS-values and the molar fraction CO_2 is ±0.3% with respect to the value of H_{SR} obtained from a laboratory GC. The reproducibility, 2σ, of H_{SR} is determined from 100 consecutive measurements, yielding 0.11%, and is independent of the gas composition.

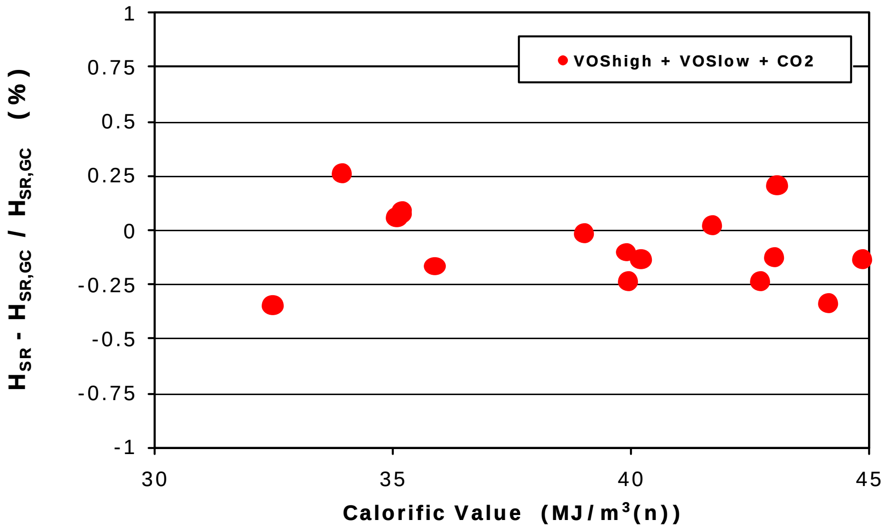

Figure 3: The relative deviation in superior calorific value measured by the correlative energy meter and a laboratory GC for common natural gases in Europe

A field test was carried out to investigate the long term stability, the reliability, the possible effect of fouling on the measuring devices and the possible occurrence of drift in the instruments reading [12]. Also the influence of changes in environmental conditions was studied. The instruments were mounted in a portable cabin, which was placed at a metering station.
A Danalyzer field gas chromatograph was mounted in the cabin as well. The reproducibility of the calorific value calculated from the compositional data generated by the Danalyzer is within ±0.02%. By comparing the results of the new correlative energy meter with the Danalyzer, the topics mentioned above (stability, fouling of meters, drift) could be monitored perfectly. The field GC updates the calorific value every 15 minutes, the correlative energy meter nearly every 10 seconds.
From the field test it can be concluded that the energy meter based on two VOS-measurements and a CO_2-measurement had a small but almost constant off set compared to the Danalyzer GC. This small off set is caused by the calibration procedure applied. The calibration parameters of the VOS-meters were adjusted so that the deviation in measured and calculated VOS for nine different gases is minimal.

Control measurements with a test gas made at regular intervals, showed clearly that both VOS-meters did not show any significant drift during the alpha field test. The other instruments (CO_2-meter and pressure and temperature transmitters) did not show any drift during the alpha field test as well.

	April and May	**June**	**July**
H_{SR} (averaged)	37.184	37.278	37.486
H_{SR} - H_{SR}(Danalyzer)	-0.141%	-0.109%	-0.138%
Reproducibility (2s)	0.102%	0.093%	0.092%

Table 1. The results of the duration tests for the VOS_{high} + VOS_{low} + CO_2 correlative energy meter compared with the Danalyzer field GC

In table 1 the results obtained during this test are summarised. Using monthly averaged values, the difference in the calorific value between the (2*VOS+CO_2) energy meter and the Danalyzer GC lies within –0.11% and –0.14%. The measured reproducibility (2σ) of the difference in calorific value between the new energy meter and the Danalyzer GC was approximately 0.1%. Because the reproducibility of the Danalyzer GC is known to be better than 0.02%, it can be concluded that the reproducibility of the new energy meters is approximately 0.1%, which corresponds with the value measured during the laboratory tests.

4.3 Field prototype

Experiences obtained during the field test and an assessment of the experimental uncertainties of the measured properties indicated the possibilities for a number of improvements. It was recognized that the successful implementation of this technique into a commercial product would benefit from the implementation of a number of improvements (see [13] for a detailed discussion).

In short these improvements are:

1. *An improvement of the reproducibility of both VOS measurements to a level of 0.0015% or better (2s-value of 20 consecutive measurements at constant gas composition).*
2. *A reduction of the vented natural gas by a factor of 9.*
3. *A decrease in response time down to a few seconds*

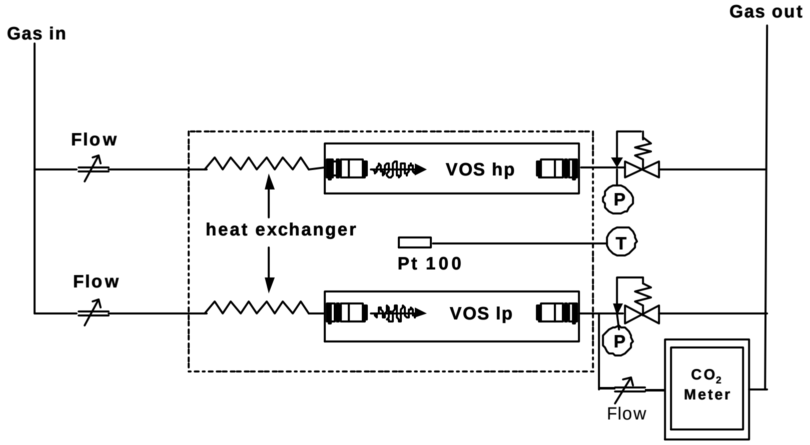

Figure 4. A schematic view of the improved energy meter. The aluminium cylinder, which is kept at 323 K, contains the components within the dotted lines.

From Figure 4 it can be concluded that the lay-out of the new energy meter is quite simple. The pressure and temperature transmitters are suitable for use in hazardous areas. The VOS-meter is a spoolpiece with transducers applied in ultrasonic flow meters for natural gas, so it can be applied in hazardous areas too. As a result, an energy meter applicable in hazardous areas can be manufactured relatively easy. Such an energy meter can be situated near a gas sampling point. This has a number of advantages: no infrastructure is required at the gas station, simple and quick installation of the energy meter is possible and a fast response is obtained with this new meter.
Taken the aforementioned improvements in consideration, Gasunie Research constructed a new field prototype, the so called VOS-Wobbemeter, which is shown in figure 5. At the top of this figure, the double VOS-meter, mounted in an Ex-E housing, is located. The CO_2-meter and electronics are each housed in Ex-D explosion proof housings and are located in respectively the middle and at the bottom of the frame. The pressure transmitters do not require any enclosure and were mounted directly onto the rack. The data are transmitted via a RS232/RS485-interface to a computer system for processing and storage.

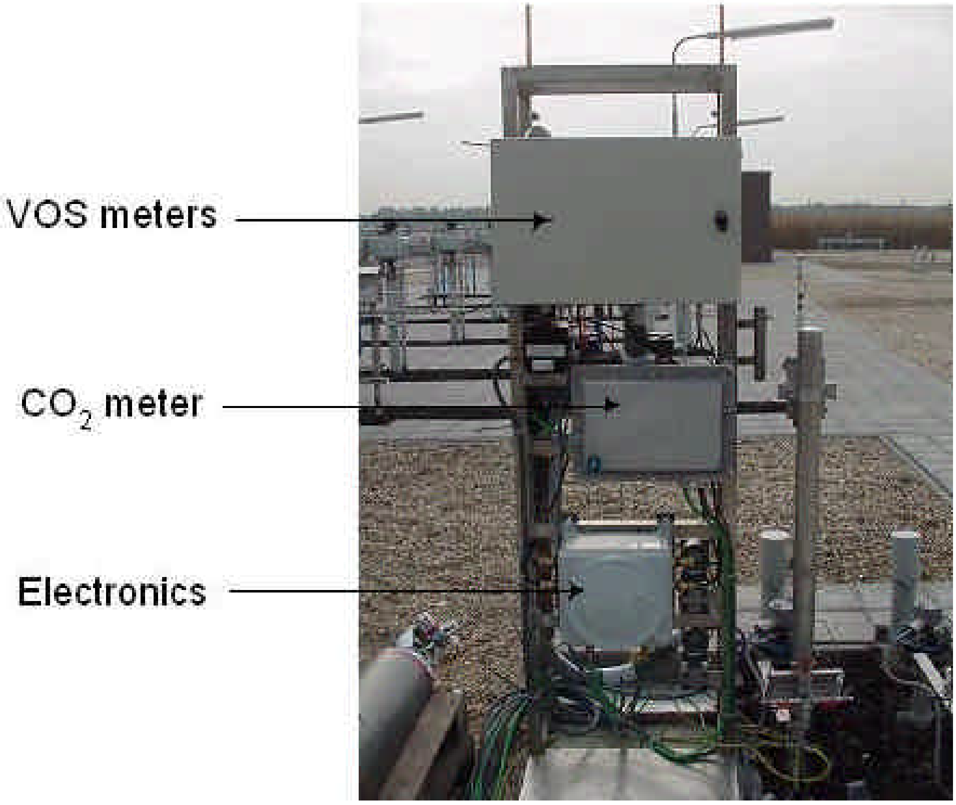

Figure 5. Field prototype of the correlative energy meter based on double VOS-measurement

4.4 Results of the beta field test
First the field prototype correlative energy meter, the VOS-Wobbemeter, was calibrated and tested at the flow calibration facility of Gasunie Research. During these tests both the superior calorific value, H_{SR}, and the Wobbe Index, W_i, were calculated and compared to the results of a Danalyzer field GC.

The VOS-Wobbemeter was manufactured in August 2002. Subsequently, it was calibrated with gas having a Wobbe Index of 43.7 MJ/m^3(n). By changing the calibration parameters of the

VOS-meter, the difference between the measured and calculated VOS for both high and low pressure was minimised. Using the analysis of a laboratory GC, the uncertainty in the calculated VOS varies between 0.01% and 0.03%. Although this only results in a small difference between the measured and calculated VOS, it sometimes results in a significant difference between the resulting Wobbe Index from a GC-analysis and the Wobbe Index determined by the VOS-Wobbemeter. Therefore, the preliminary VOS-meter calibration was followed by fine-tuning of the calibration parameters of the VOS-meters to minimise the difference between the measured and calculated Wobbe Index. After this final calibration the difference between the correlative Wobbe Index and the Wobbe Index determined from a GC-analysis was within 0.2% for a large number of gases with different compositions.

Subsequently, the new instrument was connected to a process gas stream for some weeks. The measured Wobbe Index was compared to the Wobbe Index determined from Danalyzer field GC analyses. Compared to the results of the alpha field test, the random error (2σ) in H_{SR} is reduced from 0.1% down to approximately 0.023%. The random error in density at reference conditions, ρ_R, is less than 0.001%. Finally the random error in W_i is approximately 0.025%. The uncertainty in calorific value (approximately ±0.3%) of the improved meter did not change in comparison with the first prototype. The uncertainty in the density is less then 0.02%, resulting in an uncertainty of the Wobbe Index, which is approximately ±0.3% too.

The aforementioned random errors in the measured parameters of the VOS-Wobbemeter and the corresponding uncertainty in H_{SR} were determined using 100 measurements during a short period of almost constant gas composition. The detailed results are shown in table 2. The random error of H_{SR} determined from the individual contributions (0.026%) and the measured random error in H_{SR} (0.023%) are in good agreement with each other. The results of the improvements are evident when looking to the random errors in the measured properties during the alpha and beta field test, see table 2. The small random error in H_{SR} and consequently in the Wobbe Index, W_i, is mainly resulting from the improved VOS-measurements and the better temperature control of the double VOS-meter.

	Alpha field test		**Beta Field test**	
Parameter	**Δ(Parameter) 2σ (%)**	**ΔH_{SR} (%)**	**Δ(Parameter) 2σ (%)**	**ΔH_{SR} (%)**
CO_2	0.2	0.001	0.2	0.001
VOS_H	0.006	0.075	0.0015	0.02
T_{VOSH}	0.003	0.021	0.003	0.003
P_{VOSH}	0.01	0.001	0.01	0.001
VOS_L	0.006	0.092	0.001	0.015
T_{VOSL}	0.003	0.019	= T_{VOSH}	0
P_{VOSL}	0.1	0.003	0.1	0.003
ΔH_{SR}(calculated):		***0.12%***		***0.026%***
2σ of ΔH_{SR}(measured):		***0.10%***		***0.023%***

Table 2. Variation in the calculated calorific value with respect to measured random errors (2σ) in the input parameters, during the alpha and beta field tests.

In an additional field test, the long term stability and reliability, the calibration frequency, fouling of the measuring devices and drift due to changes in the measurement conditions were studied. The outcome of the VOS-Wobbemeter was compared to a Danalyzer field gas chromatograph to monitor the long term stability. The response of the new meter was compared with a traditional Wobbe meter, the Wobbe Index Meter (WIM) of Hobré Instruments b.v [14].

The beta field test was started in November 2002 and it is still running. The VOS-Wobbemeter and a Danalyzer field GC were installed at a blending station of Gastransport Services. At this station, the blending process is controlled by WIM Wobbe meters, which are placed in temperature controlled analyser housings. The VOS-Wobbemeter was not calibrated anymore after the first calibration in August 2002. In the figure below, the results obtained with the VOS-Wobbemeter, the Danalyzer and the WIM are shown.

A cylinder was filled with natural gas and certified in the laboratory. At regular intervals the VOS-Wobbemeter was switched from process gas to this so called test gas. The Wobbe Index measured by the VOS-Wobbemeter was compared with the certified Wobbe Index.

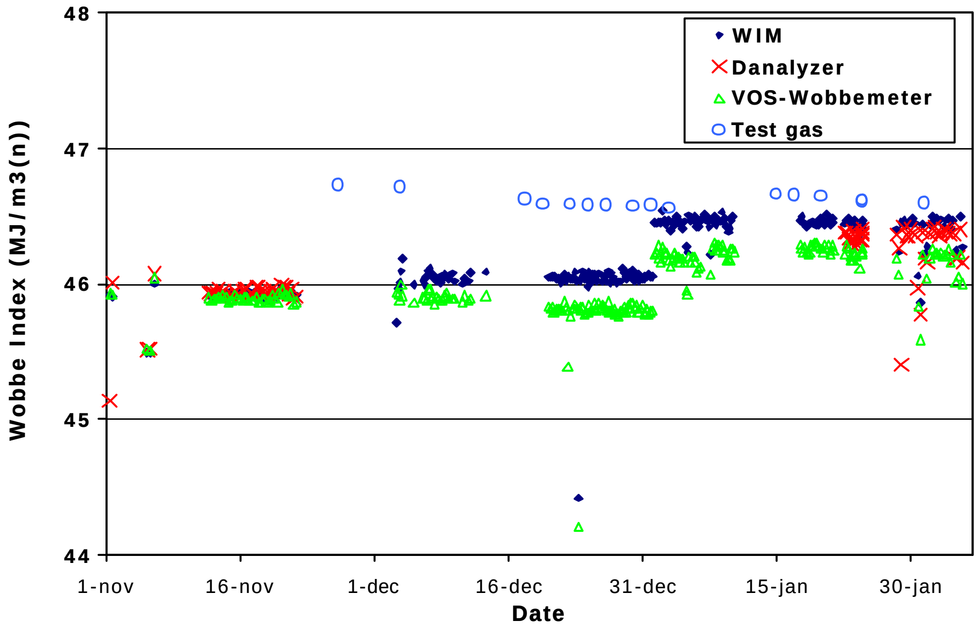

Figure 6. The Wobbe Index measured by the WIM, Danalyzer and VOS-Wobbemeter and the measured Wobbe Index of "test gas"

During a number of time intervals in figure 6, no measuring data are shown. In most cases this was caused by software failures in the commercial data acquisition programme, which is responsible for the collection of the measured data of all instruments. Once a failure occurred in the data output of the CO_2-meter, which was possibly caused by a RS232 transmission error. With respect to the instruments (VOS-meters, CO_2-meter and pressure and temperature transmitters) no failures were observed.

Most of the time the blending station produces gas with a Wobbe Index of approximately 46 $MJ/m^3(n)$. It appears that the VOS-Wobbemeter measures the Wobbe Index within 0.2%. The difference between VOS-Wobbemeter and the WIM appears to be independent of the value of the Wobbe Index.

From figure 6 some drift can be observed in the output of the VOS-Wobbemeter. To focus in more detail on this aspect, the relative deviation between the VOS-Wobbemeter and the other instruments is computed and shown in figure 7. Also the relative deviation in measured Wobbe Index for the test gas is shown in figure 7.

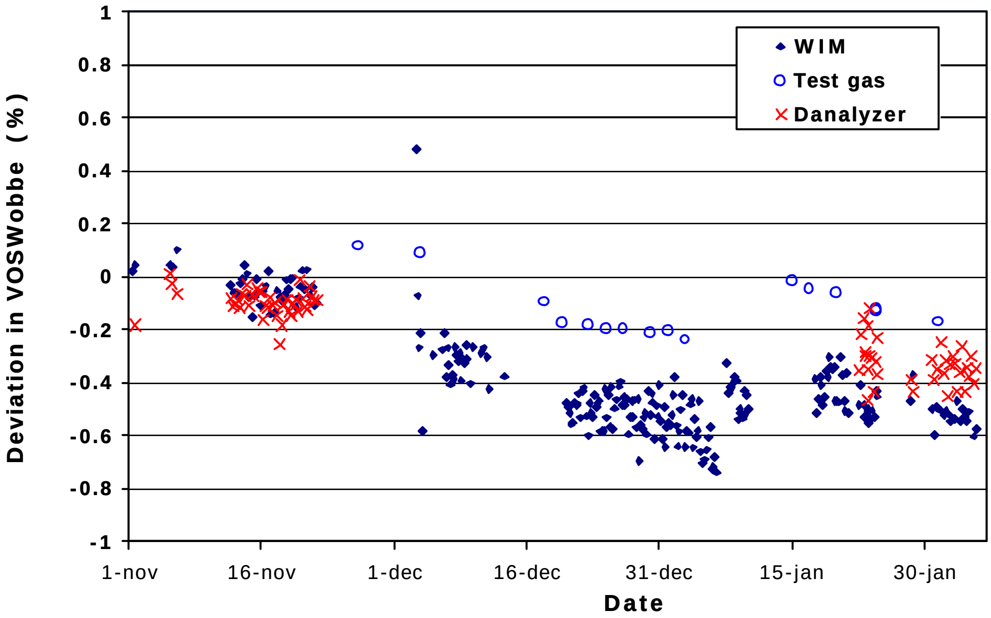

Figure 7. The relative deviation between the VOS-Wobbe and the other instruments and the deviation in Wobbe Index of the test gas

In the test period of 3 months a maximum deviation of 0.6% occurred between the VOS-Wobbemeter and the WIM. Further investigations showed that these deviations were mainly resulting from small deviations in the VOS-measurements. From figure 7 it can be concluded that the difference between the VOS-Wobbemeter and the WIM is approximately the same as the difference between VOS-Wobbemeter and test gas. Therefore, the drift is independent of the gas composition. This means that by applying a test gas measurement at regular intervals the Wobbe Index of the VOS-Wobbemeter can be corrected easily! As a matter of fact, we applied this correction and the corrected VOS-Wobbemeter data were compared with the data of the WIM Wobbe meter again. The results are shown in figure 8.

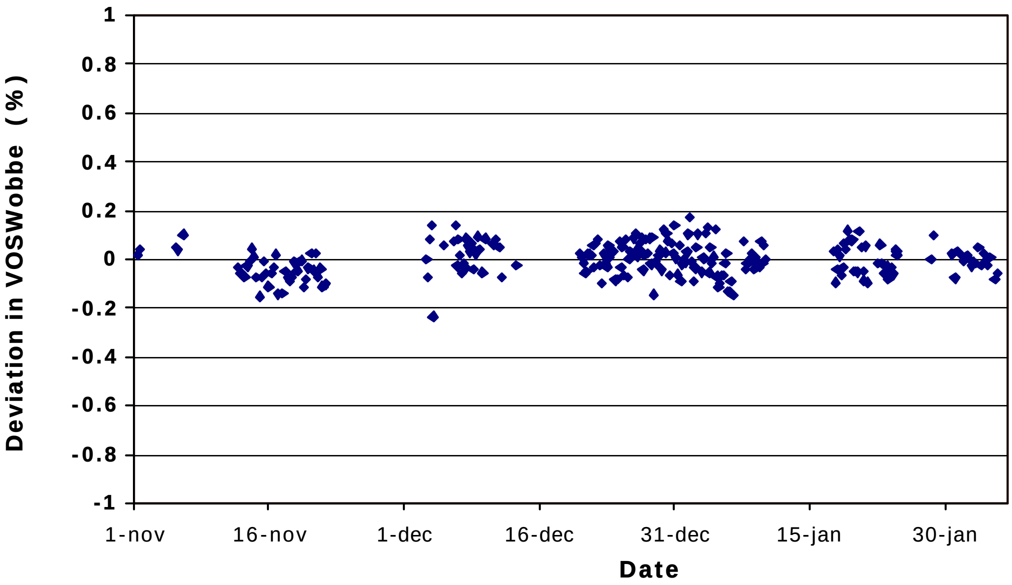

Figure 8. The relative deviation between the VOS-Wobbemeter and the WIM Wobbe meter. The VOS-Wobbemeter data were corrected using the test gas data.

4.5 Response time of the VOS-Wobbemeter

An important feature of the VOS-Wobbemeter is the response time. At blending stations a mixture consisting of two or more gasses is produced with a Wobbe Index at a pre-defined set-point. Wobbe meters control this process. Wobbe meters have to respond fast (within a few seconds) to changes in the incoming gas streams (feed forward control) or to changes in the produced gas mixture (feed back control). Therefore, a fast response and a high resolution in the measured Wobbe Index are absolute requirements for application at a blending station. A number of response time measurements showed that the response time of the new meter is approximately 6 seconds and consists of two major contributions. The time to refresh the gas in the VOS-meters is 2 - 2.5 seconds, whereas the response time of the electronics and data acquisition is 3 - 4 seconds. The latter can and will be improved in the commercial instrument. Figure 9 gives a typical view of the variation in Wobbe Index of a blended gas mixture. The measured Wobbe Index of both instruments is updated every second. The random error in Wobbe Index measured by the VOS-Wobbemeter is smaller than measured by the WIM. Furthermore, the resolution in the time-domain and in the measured Wobbe Index appears to be better for the VOS-Wobbemeter. Therefore, it can be concluded that the VOS-Wobbemeter is suitable for measuring the fast changes in the Wobbe Index that occur in a blending process. A main advantage compared to traditional Wobbe meters is that the VOS-Wobbemeter can be placed near the gas sampling point resulting in an additional gain of response time.

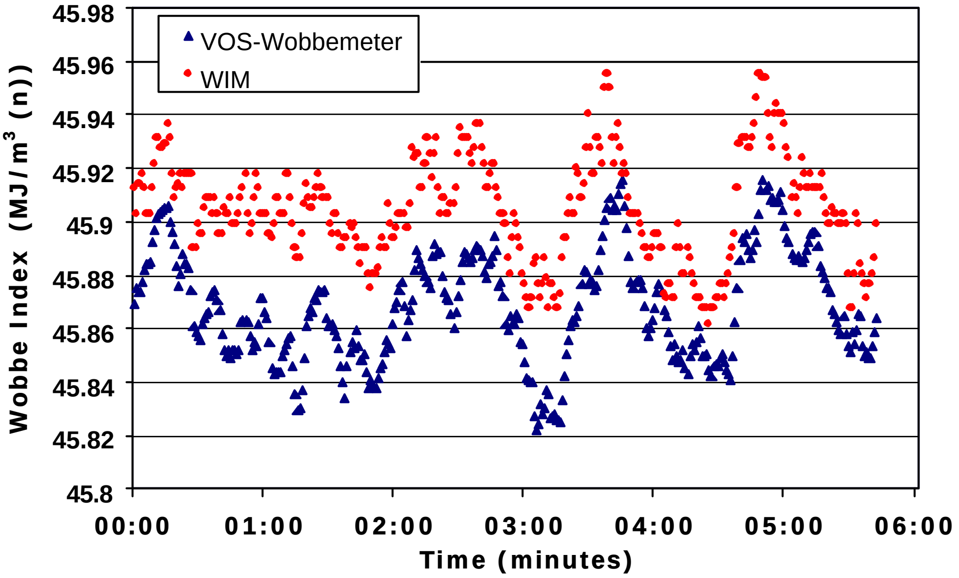

Figure 9. Changes in the Wobbe Index due to the mixing process at a blending station

5. Velocity of sound measurement by an ultrasonic gas flow meter

The principle of an ultrasonic gas flow meter is based on the measurement of the time difference between ultrasonic pulses (≈100khz) travelling downstream and upstream in the presence of a gas flow ($t_{down} < t_{up}$). The flow velocity is proportional to the reciprocal difference between these two transit times:

$$\mathbf{V = L / (2\cos\varphi) \times (1 / t_{down} - 1 / t_{up})} \tag{3}$$

Where φ is the angle between the direction of the sound pulse and the gas flow and L is the length of the acoustic path between the two transducers. The velocity of sound is proportional to the average of both transit times:

$$\mathbf{VOS = L / 2 \times (1 / t_{down} + 1 / t_{up})} \tag{4}$$

Current generation ultrasonic gas flow meters output both the gas velocity and the speed of sound while readings are updated every second.

In the past Gasunie Research performed a field test [15, 16] to determine the reproducibility of both the measured and calculated velocity of sound at Dutch metering stations equipped with multi path Q.Sonic-5 ultrasonic gas flow meters of Instromet Ultrasonics b.v.
The velocity of sound was calculated by using a computer program based on the AGA8 equation of state. The required input data comprise a detailed gas composition, the pressure and the temperature. The metering stations where the field tests were conducted are equipped with Daniel process gas chromatographs. Accurate pressure and temperature measurements are also available at these stations.
The continuous determination of the relative deviation between the measured and calculated speed of sound is called OLC-VOS (On-Line Comparison of the Velocity Of Sound) and is given by:

$$\mathbf{OLC\text{-}VOS = (VOS_{measured} - VOS_{calculated}) / VOS_{calculated}} \tag{5}$$

In figure 10 results of VOS measurements for one path (chord L1) and the corresponding OLC-VOS are shown.

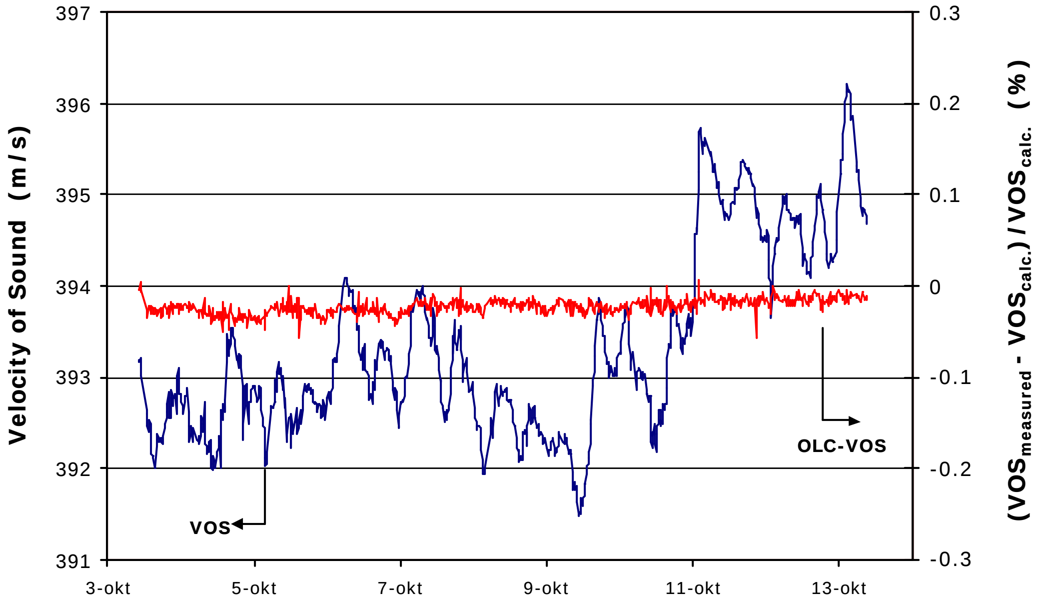

Figure 10. The measured velocity of sound of chord L1 and the difference between measured and calculated speed of sound.

During the measurement period the VOS varied between 391.5 and 396.3 m/s, a variation of more than 10%. The OLC-VOS value varied between –0.03% and –0.01%, and had a reproducibility within 0.02%. These data were obtained during normal operation of the metering station, the gas flow varied between 200.000 and 525.000 $m^3(n)/hr$. This particular station is equipped with a 20” ultrasonic flow meter, the gas velocity varied between 4.5 and 13.5 m/s.
During short intervals of almost constant gas composition the reproducibility (2σ) of the VOS measurement with the ultrasonic flow meter was determined. The reproducibility is always better than 0.01%. It is well-known that the velocity of sound measurement is influenced by the gas velocity. High gas velocities induce large turbulences in the pipe, resulting in a distortion of the acoustic path [17]. In turn, this results in both a small systematic deviation between the measured and “true” speed of sound, which can be accounted for, and a minor increase in the random deviation of the measured speed of sound. Indeed, the reproducibility increased slightly with the gas velocity (2σ = 0.002% for a gas velocity of 1 m/s and 2σ = 0.008% for a gas velocity of 11 m/s). No significant difference in reproducibility of the measured VOS has been found between the single and double reflection paths during the tests.

The uncertainty in the pressure and temperature measurement at the metering station was less then 0.1%. The reproducibility (2σ) of the pressure measurement was better than 0.01 bar and the 2σ-value of the temperature measurement was within 20 mK.

The results obtained during the ON-Line Comparison of VOS test indicate that the uncertainty and reproducibility of the measured VOS, pressure and temperature at the metering stations are comparable with values obtained for the VOS meter applied in the newly developed correlative energy meter.
Therefore, at metering stations equipped with instruments yielding performances as mentioned above, it should be possible to use these instrumental data ($VOS_{\text{high pressure}}$, $P_{\text{high pressure}}$, $T_{\text{high pressure}}$) as input for a correlative energy meter. Additionally only low pressure measurements have to be carried out ($VOS_{\text{Low pressure}}$ and CO_2) to determine the energy flow. Beside lower investment, another advantage of this concept is a reduction in gas consumption by a factor of 10, compared to the correlative energy meter with both high and low pressure VOS measurements.
Now some preliminary results to demonstrate the suitability of the above mentioned concept will be presented and discussed.

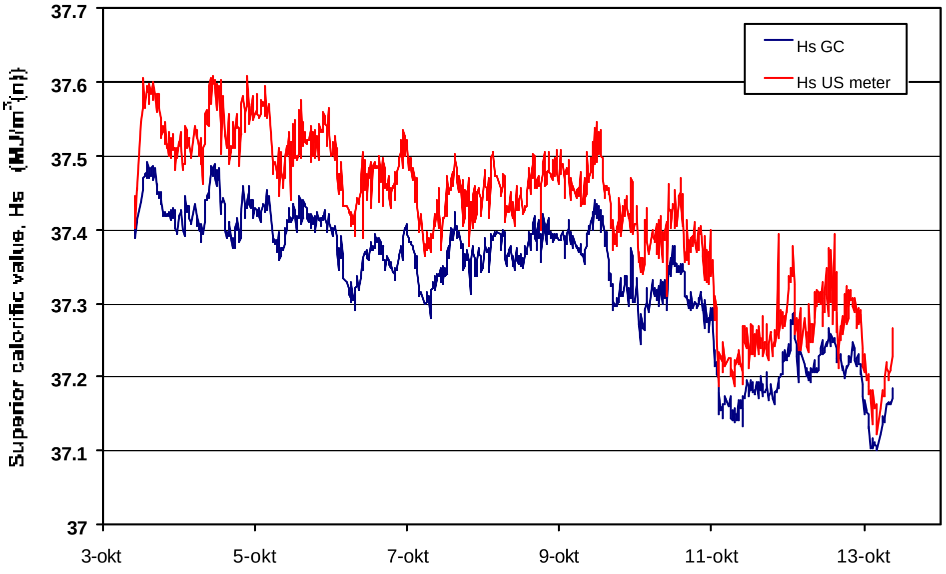

Figure 11. The superior calorific value obtained from GC data and from VOS data of an ultrasonic flow meter using the correlative method.

The On-Line Comparison VOS field test delivered data for $VOS_{high\ pressure}$, $P_{high\ pressure}$, $T_{high\ pressure}$, CO_2 molar fraction and gas composition. Low pressure VOS data were generated by using the known gas composition and taking a fixed temperature of 50 °C and a fixed pressure of 5 bar. With these input data the correlation procedure was used to calculate gas compositions and subsequently superior calorific values.

The Q.Sonic ultrasonic flow meter makes VOS data available for the 5 individual measuring paths as well as an averaged VOS. The average VOS is corrected for the VOS-dependency on the gas velocity. In figure 11 calculated values of the superior calorific value at reference conditions using averaged VOS data are shown. For comparison also H_S values from GC-data are shown. The calculated H_s has a small off-set (systematic error) which is caused by a small systematic error in the measured VOS.

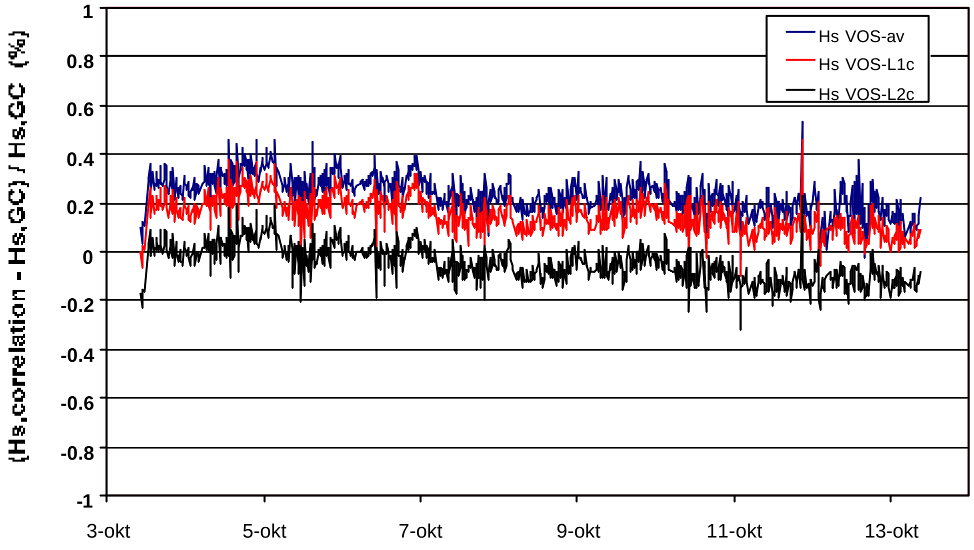

Figure 12. The difference in superior calorific value determined by the correlative method and a GC using the averaged VOS, the VOS of chord L1 and the VOS of chord L2, respectively, as input data for VOS_H

In figure 12 the difference between correlated calorific value and calorific value from GC is shown not only for the averaged VOS but also for the measured VOS of path L1 and path L2, the first being an single reflection chord and the second being a double reflection chord. These velocity of sounds were corrected for the gas velocity. The systematic error in the calorific value is caused by the systematic error in the measured VOS. A systematic error of 0.01% in VOS gives an error in the calorific value of appr. 0.075% (based on a pressure difference between both VOS measurements of 55 bar [11]). From figure 9 it appears that the maximum error in L1 is appr. 0.04%, resulting in a systematic error of 0.3% in H_S, the value shown in figure 12.

The random error in the calorific value determined with the correlative method is approximately 0.1% and is independent of the measured VOS applied.

In figure 13 the difference between the correlated calorific value and the calorific value from the GC is shown for chord L2 with (Hs VOS-L2c) and without correction (Hs VOS-L2) for changes in the measured velocity of sound due to changes in the gas velocity.

From figure 13 it is evident that velocity of sound variations due to variations in the gas velocity result in a higher uncertainty in the calculated calorific value. Therefore, the measured velocity of sound has to be corrected for the gas velocity, for this type of applications.

Because the gas passing the metering station was blended upstream, relative large variations in the composition occurred during the measurement period. Therefore, these continuous variations in composition can be used to check the reliability of the correlation model. The results are shown in figure 13 as well. It appears that the correlation model gives a small negative off-set, but almost no variations in H_S occur, despite the relative large variations in the gas composition.

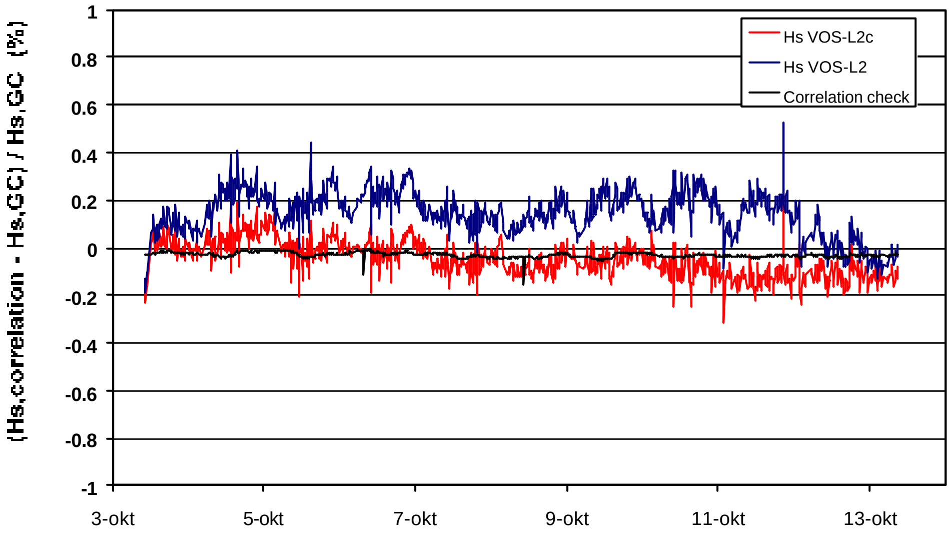

Figure 13. The effect on H_S when using the VOS corrected (Hs VOS-L2c) for changes in the gas velocity and without correction (Hs VOS-L2).
The results of a correlation check during the measuring period.

As stated before, the correlation model calculates a gas composition. This gas composition is used to calculate the velocities of sound at the measurement conditions (for P and T). Subsequently the calculated values are compared with the measured velocities of sound. In an iterative procedure the gas composition is changed until the difference between calculated and measured VOS is minimal. In principle some small differences between the actual and calculated gas composition can occur. In figure 14 both the methane concentration measured by the GC and the methane concentration calculated from the correlation model are shown. The difference between the two values is shown as well. It can be concluded that the model gives a very good estimate of the methane concentration.

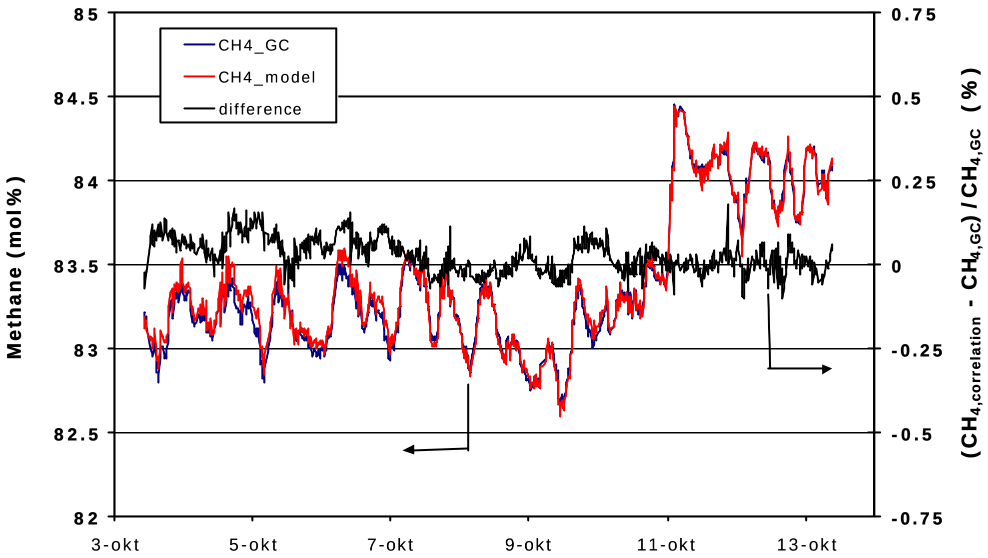

Figure 14. The measured and calculated methane concentration.

Until so far, results have been presented based on high pressure measured VOS data and low pressure *calculated* VOS data using a fixed pressure and temperature. In reality, the low pressure VOS is measured in combination with the corresponding pressure and temperature. In all measurement variables random errors will occur. Based on experimental data obtained during various tests with the correlative energy meter, it is possible to make a good estimate of the random error in the calculated superior calorific value when the low pressure VOS is measured too.

	Alpha field test **ΔP = 35 bar**		**Ultrasonic flow meter** **ΔP = 55 bar**	
Parameter	**Δ(Parameter) 2σ (%)**	**ΔH_{SR} (%)**	**Δ(Parameter) 2σ (%)**	**ΔH_{SR} (%)**
CO_2	0.2	0.001	0.2	0.001
VOS_H	0.006	0.075	0.01	0.075
T_{VOSH}	0.003	0.021	0.01	0.03
P_{VOSH}	0.01	0.001	0.01	0.001
VOS_L	0.006	0.092	0.002	0.015
T_{VOSL}	0.003	0.019	0.003	0.01
P_{VOSL}	0.1	0.003	0.1	0.003
ΔH_{SR}(calculated):		***0.12 %***		***0.1 %***
2σ of ΔH_{SR}(measured):		***0.10 %***		

Table 3. Variation in the calorific value with respect to measured random errors (2σ) in the input parameters, when using an ultrasonic gas flow meter.

The results are shown in Table 3. At the beginning of the paper it was already mentioned that the sensitivity of the correlation model with respect to small changes in the input parameters strongly depends on the difference in pressure at which both VOS measurements are operated. The pressure at the metering station with the ultrasonic gas flow meter was 60 bar, making the difference in pressure significant higher in comparison to the energy meter. That is the reason that, despite somewhat larger errors in the input data, the error in the calorific value is still within ±0.1%. The VOS measurements at low pressure are assumed to be carried out in a cell kept at 50 °C, so that random errors in VOS and temperature are comparable with those obtained during the beta field test.

It can be concluded that velocity of sound data measured with an ultrasonic flow meter in combination with accurate values for pressure and temperature can be used as input parameters for the correlative model to calculate the gas composition and gas properties.

Advantages are:

- The decrease in gas consumption by approximately a factor of 10 compared to the use of the double VOS-meter.

- A decreased sensitivity in H_S with respect to changes in the input parameters if the pressure at the metering station is above 40 bar, resulting in a more stable value for H_S.

However, a disadvantage of this set-up is that the VOS-data are obtained at two different temperatures, resulting in additional systematic errors due to differences in the measured temperature and the true temperature for each VOS measurement. By using a double VOS-meter, which is kept at a constant temperature, this kind of errors can be avoided.
Another disadvantage is a small temperature dependency of the measured VOS, we did observe previously. A small change in VOS due to a change in gas temperature is amplified approximately 10 times in the determined calorific value.

6. CONCLUSIONS

The new correlative energy meter, based on velocity of sound measurements at 40 and 5 bar and a CO_2 measurement, seems a promising instrument to determine the energy value of gas streams at production sites and custody transfer stations. Due to its short response time of only a few seconds, it is also an ideal instrument to determine the energy value (Wobbe Index) of natural gas streams in process control applications such as for example at blending stations. Newly developed, low-volume and highly accurate velocity of sound meters provide velocity of sound data, which deviate less than 0.04% from the calculated velocity of sound with a reproducibility within 0.002%.

A sensitivity study revealed that systematic errors in the velocity of sound measurements at high and low pressure result in errors with the same order of magnitude but opposite signs in the calculated calorific value. The same holds for the temperature measurement in both VOS-meters. Random errors in the velocity of sound measurements result in a 10 times higher error in the calorific value.

The calorific value, H_{SR}, and the Wobbe Index, W_I, can be determined with a maximum uncertainty of ±0.3% with respect to a laboratory GC, by measuring the molar fraction CO_2 and the velocity of sound at two pressures ($P_H - P_L > 35$ bar). Under laboratory conditions the reproducibility was ±0.12%. During the alpha field test the reproducibility of the new energy meter was ±0.1%.

A number of improvements were carried out and at the moment the improved meter is tested in a beta field test at a blending station. The results of the tests undertaken so far, indicate that the uncertainty (< ±0.3%) and measured reproducibility (±0.02%) of the improved correlative energy meter are fully comparable with highly accurate field GC's used in custody transfer applications to day. The causes for the observed small drift effect in the new meter are under investigation, however a drift correction can be made easily, by measuring a natural gas with known Wobbe Index at regular intervals.

Advantages of the new instrument are: (i) it does not require an analyser housing, (ii) it can be positioned near the pipe, so there is a short sample line, (iii) a fast response time (5 seconds) (iiii) also density and CO_2 are determined, therefore no additional instruments for these measurements are required anymore. Furthermore, the costs of ownership for the new system are considerably lower compared to current energy meters and Wobbe Index meters.

At stations with an ultrasonic gas flow meter, the flow meter can provide the VOS high pressure input data for the correlation model. The random error in calorific value and other gas properties will be approximately ±0.1%, on the condition that accurate temperature and pressure data are available too at the metering station.

7. OUTLOOK

Instromet International has already started with the manufacturing of an energy meter based on the measuring principle described in this paper. The picture below presents the "**EnSonic**", the new energy metering system for natural gases based on a double speed of sound measurement.

Figure 15: A picture of the **EnSonic**, the novel energy meter of Instromet International

Using highly accurate, state of the art ultrasonic technology the velocity of sound at high (approx. 30 ~ 40 bar) and low (approx. 2 ~ 3 bar) pressure is measured. The high accuracy of +/- 0.3 % for the Wobbe Index and +/- 0.1% for the (relative) density and the fast response (< 5 sec) open up new 'real time' applications were currently available gas chromatography is either too slow or too expensive. Furthermore, this stand alone system is ideally suited for field mounted applications without the need for any additional conditioning. The inherent insensitivity of the ultrasonic measurement for pollution allows for the use in off-shore or other harsh environments. All measurement data can easily be accessed via the MODBUS output and up to 8 freely programmable analog outputs can be provided by connecting the system to an Instromet FC2000 flow computer (displayed at the right of the energy meter).

8. NOTATION

d	relative density of natural gas to air at reference conditions
H_{SR}	superior calorific value under reference conditions, MJ/m^3(n)
P	Pressure, bar
T	Temperature, K
VOS	Velocity of sound of natural gas, m/s

W_i	Wobbe Index, MJ/m^3(n)
Z	Compressibility of natural gas
$\rho_{R,gas}$	density of natural gas at reference conditions, kg/m^3(n)
$\rho_{R,air}$	density of air at reference conditions, kg/m^3(n)

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